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Ecological and economic performance of integrated pest management as a pathway to organic agriculture in rice farming in Indonesia

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Abstract

Sustainable rice production in tropical systems increasingly depends on farming strategies that balance productivity, input efficiency, and environmental integrity. Integrated pest management (IPM) is widely promoted as a pathway toward safer and more sustainable rice (paddy) cultivation, yet evidence on its economic performance and efficiency relative to conventional practices remains mixed, particularly in Indonesia. This study compares the economic efficiency of IPM and non-IPM rice farmers in Kampar District, Kampar Regency, Riau, Indonesia using cost-based stochastic frontier analysis on cross-section survey data from 100 households. The results show that IPM farmers achieve significantly higher economic efficiency (0.67) than non-IPM farmers (0.46). This is primarily due to greater technical efficiency, despite similar levels of allocative efficiency. IPM practices reduce pesticide expenditure by 63.1 % and increase yields by 43.4 %, but they require substantially more labour – highlighting a key barrier to adoption in areas undergoing rural labour-saving innovations. Strengthening IPM-aligned networks and enhancing farmer training could help to accelerate progress towards ecologically resilient and economically competitive rice systems in Indonesia.

Keywords: agroecological transition, stochastic frontier, smallholder farming, tropical rice systems, sustainability

1 Introduction

Rice (*Oryza sativa*) plays a pivotal role in global food security, feeding more than half of the world's population, particularly across Asia. As a primary staple crop, rice contributes significantly to rural livelihoods and national economies in developing countries such as Indonesia, which ranks among the world's top three rice producers (FAO, 2022). However, rice farming systems are increasingly challenged by environmental degradation, climate variability, soil fertility decline, and pest outbreaks, all of which threaten productivity and long-term sustainability (Kumar *et al.*, 2022). Among these, the unsustainable use of chemical pesticides stands out as a critical issue, causing negative externalities such as environmental pollution, human health risks, and rising production costs (Anderson *et al.*, 2019; Purnama *et al.*, 2023; Sapbamrer *et al.*, 2023; Wolfe & Marsit, 2023; Malhat *et al.*, 2024).

Synthetic chemical pesticides, while effective in mitigating pest damage, are increasingly recognised as a double-edged sword. Over-reliance on pesticides can lead to the development of pest resistance, contamination of water and soil resources, and negative health impacts on farmers and consumers (Popp *et al.*, 2013). Moreover, excessive pesticide use can diminish the overall technical efficiency of farming systems by misallocating resources and increasing production costs without proportionate gains in yield (Adem, 2023). These challenges are particularly pronounced in Southeast Asia, where pesticide usage is among the highest globally, and smallholder farmers often lack access to training on sustainable practices (Pretty *et al.*, 2018).

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Against this backdrop, integrated pest management (IPM) has emerged as an ecologically oriented alternative to synthetic pesticide-intensive farming. By combining biological, cultural, and mechanical pest control methods with rational pesticide use, IPM aims to maintain productivity while reducing environmental and health risks (Abbas *et al.*, 2022; Purnama *et al.*, 2024a; 2024b; Anggrayni *et al.*, 2025). Empirical studies show that IPM can reduce pesticide applications and maintain or even increase yields (Pecenka *et al.*, 2021), yet adoption varies widely due to socioeconomic and institutional constraints (Peshin *et al.*, 2023). Although national IPM programmes in Indonesia have promoted sustainable cultivation practices, evidence on their local-level economic performance remains limited (Purnama *et al.*, 2023).

While many studies have examined the agronomic and environmental benefits of IPM, with fewer examining its impact on systemic cost efficiency – encompassing technical, allocative, and economic efficiency (Hidayati, 2019; Hoque *et al.*, 2019; Bairagi *et al.*, 2021). This perspective is crucial in smallholder systems, where input decisions are shaped by ecological and market uncertainties. Whether IPM enhances economic viability under real production conditions remains unclear, leaving a critical research gap in Southeast Asia.

This study addresses that gap by comparing the systemic cost efficiency of IPM and non-IPM rice farmers in Kampar District, Riau Province, Indonesia, using a stochastic cost frontier framework. By integrating input–output data with socio-economic factors such as education, extension participation, and land tenure, it evaluates how IPM influences farm-level performance under local constraints. Rather than assessing a transition to organic farming, the study investigates whether IPM supports economic sustainability whilst reducing pesticide dependence – an issue relevant to broader agroecological debates.

The findings aim to inform evidence-based policy on sustainable pest management and farmer support systems. Whilst conceptually linked to sustainability agendas such as SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), the primary contribution lies in determining whether IPM is both environmentally beneficial and economically efficient in smallholder tropical rice systems.

2 Materials and methods

2.1 *Study area and context*

This study was conducted in Kampar District, Riau Province, Indonesia, one of the major rice-producing areas in the region. Rice farming in Kampar is dominated by smallholder systems operating under contrasting pest management practices, ranging from IPM to pesticide-intensive conventional approaches. The district is agroecologically diverse and characterised by recurrent challenges such as pest outbreaks, seasonal water constraints, and declining soil quality, making it a suitable setting for examining sustainability-oriented farm performance.

Rice production in Kampar, as in much of Southeast Asia, is strongly shaped by rising input costs, particularly for pesticides and fertilisers, which constitute a substantial share of production expenses. Although national programmes have promoted IPM through farmer field schools (FFS), adoption remains uneven due to differences in farmer education, institutional engagement, and access to extension services. These local variations provide an opportunity to assess how IPM adoption relates to technical, allocative, and economic efficiency at the farm level. Kampar also reflects broader sustainability trade-offs faced by smallholder farmers, who must balance cost control, yield stability, and environmental considerations. From this perspective, the study area represents a socio-ecological system in which economic and ecological decisions are closely interconnected. Situating the analysis in this context allows the study to contribute to wider discussions on sustainable pest management and cost efficiency in smallholder rice systems (Pretty *et al.*, 2018; Autio *et al.*, 2021; Çakmakçı *et al.*, 2023).

2.2 *Sample selection*

The study employed a purposive sampling technique to ensure a balanced representation of IPM and non-IPM rice farmers. Villages were first selected based on the documented presence or absence of IPM programmes recorded by the local agricultural extension office. This step ensured that the sample captured variation in IPM exposure rather than clustering only in IPM-active areas. Within each selected village, farmers were then shortlisted based on rice farming as their primary livelihood, and simple random sampling was applied to select respondents proportionally from the identified lists.

IPM farmers were identified based on participation in FFS and adherence to IPM principles, such as reduced reliance on synthetic pesticides, adoption of biological control, and healthy-crop practices. Non-IPM farmers were selected from the same and neighbouring villages to control for agro-environmental variability (soil type, irrigation access, and seasonal calendar). A total of 100 farmers participated in the study, comprising 38 IPM and 62 non-IPM practitioners.

This two-stage procedure minimised systematic differences between villages while allowing variation in IPM adoption. Nonetheless, because IPM farmers are less numerous than non-IPM farmers in the study area, the sample reflects real adoption proportions rather than a perfectly balanced split. Therefore, representativeness is maintained for local conditions, while potential selection bias is acknowledged and discussed in the limitations.

2.3 Data collection

Primary data were collected through structured face-to-face interviews using a validated and pre-tested questionnaire. The instrument captured comprehensive information on socioeconomic characteristics (e.g., age, education, farming experience), input quantities (e.g., land, labour, seed, fertilisers, pesticides), as well as input prices, total production costs, and output values. These variables enabled the estimation of allocative and economic efficiency using a dual frontier approach involving both cost and revenue data.

To complement the quantitative data, qualitative insights on perceived environmental changes were also collected, focusing on pesticide application behaviour, the use of natural pest control methods, and farmer perceptions regarding changes in soil and water quality (Çakmakçı *et al.*, 2023; Akinbode *et al.*, 2024). These indicators provide contextual depth to assess emergent system behaviours under complex pest management regimes. Farmers were also asked about non-monetary ecological practices, such as the use of refugia, trap plants, and manual pest removal techniques.

Secondary data – including historical cost structures and local pest management trends – were obtained from district agricultural extension offices. In addition, several variable constructs and baseline technical efficiency findings were cross-referenced from a previously published study on rice farming in Kampar (Amalia *et al.*, 2023), which serves as a technical foundation for this economic efficiency analysis. Ethical approval for this study was obtained from the Research Ethics Committee of Universitas Lancang Kuning. All respondents participated voluntarily and provided informed consent prior to data collection.

2.4 Cost efficiency analysis framework

This study applied a stochastic cost frontier (SCF) approach to estimate the cost efficiency of rice farming systems, with a focus on comparing IPM and non-IPM practices. The cost efficiency framework integrates both technical and allocative dimensions to capture the full spectrum of farm-level economic performance under varying input prices and environmental constraints. The SCF model assumes that each farmer seeks to minimise the total cost of production for a given output level, conditional on input prices. The functional form of the cost frontier is based on the Cobb-Douglas specification and expressed as:

$$\ln C_i = \alpha_0 + \sum_{j=1}^{k} \alpha_j \ln w_{ji} + \beta \ln Y_i + v_i + u_i \tag{1}$$

where C_i denotes the total production cost for farmer i, w_{ji} represents the unit price of the j-th input (such as labour, fertiliser, pesticides, and seeds), and Y_i is the total output of rice ($\mathrm{kg\,ha^{-1}}$). The parameters α_j and β capture the cost elasticities, while the error term is decomposed into a symmetric random component $v_i \sim N(0, \sigma^2)$ and a one-sided inefficiency term $u_i \geq 0$, which reflects deviations from the minimum possible cost due to allocative or managerial inefficiency.

In line with the conceptual framing of systemic cost efficiency introduced earlier, cost efficiency (CE) is operationalised in this study using a stochastic cost frontier approach and derived from the inefficiency component as:

$$CE_i = \exp(-u_i) \tag{2}$$

A CE value of 1 indicates a fully cost-efficient farmer, while values closer to 0 reflect greater inefficiency in minimising costs for a given level of output and input prices.

To evaluate the sources of inefficiency, we also incorporated technical efficiency (TE) scores from our prior stochastic production frontier analysis (Amalia *et al.*, 2023), which measures the ability of farmers to produce the maximum feasible output from given input quantities. By combining CE and TE, we computed allocative efficiency (AE), which represents the ability to use inputs in cost-minimising proportions:

$$AE_i = \frac{CE_i}{TE_i} \tag{3}$$

Following Farrell (1957), overall economic efficiency (EE) was defined as the product of technical efficiency (TE) and allocative efficiency (AE) (EE = TE × AE). This decomposition allows inefficiency to be attributed either to suboptimal input use (TE) or to inappropriate input allocation given relative prices. Allocative efficiency was obtained as AE = CE / TE. All efficiency estimates were based on observed input–output data reported in Tables 2 and 4, ensuring that the values presented in Table 5 are fully traceable to farm-level observations.

2.5 Statistical estimation

The stochastic cost frontier models for IPM and non-IPM farmer groups were estimated using the maximum likelihood estimation (MLE) technique, implemented in STATA 17. The validity and goodness-of-fit of the models were tested using log-likelihood ratio tests to compare nested specifications. To ensure the robustness of parameter estimates, multicollinearity among input price variables was assessed using the Variance Inflation Factor (VIF), with all values remaining below the critical threshold of 10.

Technical efficiency scores from the stochastic production frontier (Amalia *et al.*, 2023; Rauniyar & Kim, 2025) were incorporated to compute allocative and economic efficiency for each farmer. Sensitivity checks were also conducted by re-estimating the models with alternative variable specifications (e.g., excluding interaction terms or separating pesticide categories) to confirm the consistency of the efficiency scores across model variants. The analytical approach reflects a complexity-informed framework, recognising that farm-level systemic cost efficiency is shaped not only by economic variables but also by institutional, cognitive, and ecological feedback mechanisms. All procedures followed established econometric practices in frontier efficiency analysis.

3 Results

3.1 Respondent characteristics

Table 1 summarises the socioeconomic characteristics of the sampled IPM and non-IPM rice farmers in Kampar District. Overall, the two groups differed markedly in terms of educational background, institutional engagement, land tenure, farming experience, and pest management behaviour. These contrasts indicate underlying structural differences that are likely to shape farm-level decision-making, particularly in relation to input allocation, adoption of ecological practices, and responsiveness to extension services.

Table 1: *Socioeconomic characteristics of integrated pest management (IPM; n = 38) and non-IPM (n = 62) rice farmers in Kampar District, Indonesia.*

Variable	*IPM (%)*	*Non-IPM (%)*
Age group 45–64 years	73.7	74.2
Formal education ≥ junior high school (≥ 7 yrs)	55.2	41.8
Main occupation: Rice farmer	60.5	62.9
Own land	47.3	12.9
Farming experience > 20 years	44.7	30.6
Group membership	100.0	88.7
Attended farmer field school	47.3	0.0

Institutional engagement differed sharply between groups. IPM farmers consistently demonstrated stronger integration within farmer networks and extension systems, whereas non-IPM farmers participated less actively. Participation in FFS – the main vehicle for IPM dissemination – was exclusive to the IPM group, indicating a clear divide in access to experiential learning and ecological knowledge sharing. This institutional gap is likely to influence differences in pest management behaviour, decision-making, and responsiveness to innovation.

Land tenure patterns were also distinct. IPM farmers were more likely to cultivate their own land, whereas non-IPM farmers commonly operated through rental or borrowed arrangements, a factor that may discourage long-term investment in soil and pest management improvements. Differences in farming experience followed a similar pattern, with a higher tendency among IPM farmers to have long-term exposure to rice cultivation, which may improve familiarity with seasonal pest dynamics.

Although all respondents were rice farmers by selection, non-IPM farmers more frequently engaged in additional livelihood activities (e.g., rubber tapping or horticulture). This diversification may result in divided managerial attention, potentially influencing input-use planning and record-keeping practices.

Differences in pesticide application were also observed. On average, IPM farmers applied pesticides 2.4 times per season, whereas non-IPM farmers applied them 4.2 times. Furthermore, IPM farmers employed a wider range of ecologically based pest control methods, including fermented plant extracts, locally prepared biopesticides, insect traps, scarecrows, and insect nets. They also undertook habitat management through the planting of flowering species as refugia to attract natural enemies, consistent with ecological principles found in tropical agroecology.

Fig. 1: *Ecological pest control practices applied by integrated pest management (IPM) farmers in tropical rice fields: (A) Preparation of botanical biopesticides from local ingredients; (B) manual pest trapping using modified plastic bottles; (C) active pest collection using large insect nets; (D) establishment of flowering refugia along bunds to attract beneficial insects; (E) construction of scarecrows to protect rice fields from bird attacks.*

These integrative strategies are summarised visually in Fig. 1, which illustrates the various ecological pest control practices employed by IPM farmers. These include the construction of bottle traps, installation of large insect nets, use of natural repellents, and the planting of flowering strips to attract beneficial predators. The figure reflects the multi-faceted nature of ecological knowledge applied in the field.

3.2 Cost structure comparison

Table 2 compares the average production cost structure per hectare between IPM and non-IPM farmers. IPM systems were associated with slightly higher total production costs, primarily reflecting a reallocation of inputs away from synthetic pesticides towards labour-intensive ecological practices and organic inputs. In contrast, non-IPM farmers relied more heavily on synthetic pesticides and inorganic fertilisers.

Labour constituted the largest cost component in IPM systems, underscoring the skill- and monitoring-intensive nature of ecological pest management. Although IPM farmers continued to apply inorganic fertilisers, these were used alongside organic amendments, indicating a gradual reduction in chemical dependency rather than complete substitution. This balanced input strategy is consistent with a transition-oriented approach to sustainable nutrient management.

Table 2: *Average cost structure per hectare by farming type (IDR).*

Input category	*IPM farmers (IDR/ha)*	*Non-IPM farmers (IDR/ha)*
Land rent	750,000	750,000
Seed	645,105	504,241
Organic fertiliser	1,148,842	559,862
Inorganic fertiliser	1,038,802	785,344
Natural pesticide	100,737	–
Synthetic pesticide	382,526	1,035,172
Labour	5,082,895	3,987,552
Total cost	9,148,907	7,622,171

Note: IDR = Indonesian Rupiah. Exchange rate reference: IDR 15,500 ≈ USD 1 (≈ EUR 0.92). Conversion provided for international comparability of monetary values.

The stochastic cost frontier results (Table 3) further confirm the central role of labour, seed prices, and synthetic pesticide costs in explaining cost variation across farms. The insignificance of organic and natural pesticide costs suggests that these inputs contribute more to ecological functioning than to short-term cost pressure.

Table 3: *Estimated cost function parameters for IPM and non-IPM rice farmers.*

Input variable	*Estimated coeff.*	*Sign. level*
Land rent	0.012	NS
Seed price	0.164	***
Organic fertiliser	0.011	NS
Inorganic fertiliser	0.018	**
Natural pesticide	0.004	NS
Synthetic pesticide	0.039	**
Labour wage	0.741	***

Note: NS = not significant, $^{***}p < 0.01$, $^{**}p < 0.05$.

3.3 Output and revenue performance

Table 4 shows that IPM farmers achieved an average yield of 3,696 kg ha^{-1}, compared to 2,577 kg ha^{-1} for non-IPM farmers. Both groups sold their paddy at the same market price of IDR 4,500/kg. Accordingly, IPM farmers attained an average gross revenue of IDR 16,633,440 ha^{-1}, substantially higher than the IDR 11,595,105 ha^{-1} generated by non-IPM farmers. After deducting production costs, net income stood at IDR 7,484,533 ha^{-1} for IPM farmers and IDR 3,972,934 ha^{-1} for non-IPM farmers.

Table 4: *Output and revenue performance of IPM and non-IPM rice farmers.*

Component	*IPM (n = 38)*	*Non-IPM (n = 62)*
Rice yield (kg ha^{-1})	3,696	2,577
Selling price (IDR kg^{-1})	4,500	4,500
Gross revenue (IDR ha^{-1})	16,633,440	11,595,105
Total production cost (IDR ha^{-1})	9,148,907	7,622,171
Net income (IDR ha^{-1})	7,484,533	3,972,934
Benefit-Cost Ratio (BCR ratio)	1.82	1.52

For conversion rate IDR to USD / EUR see Table 2.

3.4 Allocative and economic efficiency

Efficiency estimates from the stochastic cost frontier model (Table 5) demonstrated that average allocative efficiency (AE) among IPM farmers was 0.67, nearly identical to the 0.66 observed among non-IPM farmers, indicating that both groups faced challenges in optimally allocating inputs. This limited difference should be interpreted with caution given the smaller sample size of IPM farmers and the overall low allocative efficiency across groups. Nonetheless, distributional patterns showed that a slightly larger proportion of IPM farmers had AE scores above 0.7 (50 % vs. 45.16 %). Although labour cost was substantially higher among IPM farmers, this reflects the labour-intensive nature of ecological pest management, which requires regular field scouting, manual pest collection, preparation of botanical extracts, and habitat management activities. Whilst the study did not quantify labour use in hours or days per hectare, interviews with farmers indicated that IPM adopters generally spent more time on monitoring-based and manual pest control than non-IPM farmers. This qualitative pattern explains the higher labour expenditure without implying inefficiency.

Table 5: *Allocative and economic efficiency scores of IPM and non-IPM rice farmers.*

	Farmers	
Efficiency indicator	*IPM*	*Non-IPM*
Mean allocative efficiency (AE)	0.67	0.66
Maximum AE	0.98	0.97
Minimum AE	0.27	0.11
Standard deviation (AE)	0.15	0.12
Mean economic efficiency (EE)	0.67	0.46
Maximum EE	0.98	0.86
Minimum EE	0.27	0.01
Standard deviation (EE)	0.13	0.15

Derived from stochastic cost frontier model estimation.

4 Discussion

The observed differences between IPM and non-IPM farmers indicated a consistent pattern of stronger enabling conditions among IPM practitioners. Higher educational attainment, closer institutional engagement through farmer groups and farmer field schools, more secure land tenure, and longer farming experience jointly shaped farmers' capacity to respond to ecological risks, input prices, and management innovations. These factors do not operate in isolation but reinforce one another, creating a structural environment that supports adaptive and knowledge-intensive pest management. This finding aligns with previous studies emphasising the role of education and institutional exposure in facilitating threshold-based pesticide use and improved farm decision-making (Pretty *et al.*, 2018; van den Berg *et al.*, 2020; Mdiya *et al.*, 2024). This pattern suggests a broader systems-based approach to pest management that integrates habitat management and contextual knowledge, aligning with tropical agroecological concepts such as tel-ajakan (Wulandari & Syarifah, 2021; Purnama *et al.*, 2025).

Within this enabling environment, IPM farmers relied less on synthetic pesticides and more on non-chemical control strategies, reflecting a broader ecological management orientation. Although this study did not directly measure pesticide residues, ecological indicators, or health outcomes, the lower frequency of pesticide applications suggested plausible environmental and human-health implications. Reduced pesticide use has been widely associated with lower contamination risks for soil, water, and farm workers (Pretty *et al.*, 2018; Pecenka *et al.*, 2021), which is particularly relevant in Kampar, where rice fields are located near settlements and waterways. These implications should be interpreted as theory-driven expectations rather than empirically verified outcomes of the present study, highlighting the need for future field-level environmental and exposure monitoring.

The cost structure analysis further suggested that IPM systems are not strictly cost-minimising but cost-redistributing. Savings from reduced synthetic pesticide use were reallocated to labour inputs required for pest monitoring, botanical preparations, and ecological practices. The strong contribution of labour costs in the stochastic cost frontier is consistent with earlier observations that ecological pest management substitutes chemical dependence with human skill, attention, and management intensity (Pretty *et al.*, 2018; Pecenka *et al.*, 2021). However, the labour requirements of IPM must be interpreted within the structural context of Kampar District, where seasonal out-migration to oil-palm plantations and an ageing farming population constrain the availability of both household and hired labour. These constraints help explain why some farmers continue to rely on pesticide-intensive strategies that are less labour demanding, despite higher long-term costs.

Despite these labour constraints, IPM adoption in Kampar was associated with higher yields and stronger income performance, indicating that ecological intensification can remain economically viable under smallholder conditions. Comparable studies by Sharma *et al.* (2019) and Zheng *et al.* (2022) report similar patterns, where IPM adoption was linked to improved farm income and access to markets for low-residue or eco-labelled rice.

Efficiency analysis indicated that both IPM and non-IPM farmers face similar structural limitations in optimising input allocation. The near-identical allocative efficiency scores should not be interpreted as a meaningful performance gap but rather as evidence of systemic constraints, including limited access to reliable price information, weak bargaining positions in input markets, and the absence of advisory services focused on cost optimisation. This interpretation is consistent with findings from Hoque *et al.* (2019) and Bairagi *et al.* (2021), who showed that price awareness alone is insufficient to achieve allocative efficiency without institutional support. The wide variation in economic efficiency among non-IPM farmers further suggested latent inefficiency arising from gaps in support systems and adaptive capacity rather than from behavioural differences alone (Bibi *et al.*, 2021).

This study has several methodological limitations that must be taken into account when interpreting the results. First, the cross-sectional design only captured differences between groups at a single point in time, thus preventing definitive causal inference regarding the effects of IPM. The findings should therefore be interpreted as statistical associations rather than evidence of causal impact. Second, although purposive sampling ensured adequate representation of both IPM and non-IPM farmers, the approach may introduce selection bias because farmers participating in FFS or group-based learning may already be more knowledgeable or motivated. Third, the stochastic cost frontier model does not correct for potential endogeneity, such as self-selection into IPM adoption by farmers who are already more efficient or better resourced. Future studies employing longitudinal tracking, quasi-experimental approaches, or instrumental-variable designs would be valuable to more rigorously identify causal mechanisms linking IPM adoption and farm-level efficiency.

5 Conclusion

This study demonstrated that integrated pest management (IPM) was associated with improved economic performance and potential ecological benefits in smallholder rice farming in Kampar District, Indonesia. IPM adoption was linked to more efficient input use and stronger income performance, indicating that ecological pest management practices can be economically viable for smallholders. However, the findings should be interpreted with caution, as the analysis is based on a limited number of IPM farmers and a single study location and therefore reflects associations rather than causal effects. Future multi-site studies with larger samples and longitudinal designs are required to validate these patterns and assess long-term sustainability outcomes. Strengthening farmer training, institutional support, and policy incentives may further support the scaling of IPM as a pathway towards more sustainable rice production.

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Author contribution

Amalia Amalia: conceptualisation, data curation, formal analysis, investigation, methodology, funding acquisition, writing – original draft. Indra Purnama: conceptualisation, methodology, supervision, validation, project administration, funding acquisition, writing – review & editing. Rini Nizar: investigation, resources, data curation, visualisation. Hamdan Yasid: software, formal analysis, validation. Anisa Mutamima: writing – original draft, visualisation, literature review, validation.

Conflict of interest

The authors declare that they have no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to confidentiality agreements with participants, raw datasets are not publicly archived. Anonymised summary data and the analytical code for the stochastic frontier analysis can be shared for academic and non-commercial purposes.

Ethics approval and informed consent

This study was conducted in accordance with ethical standards for research involving human participants. The research protocol was reviewed and approved by the Ethics Committee of Universitas Lancang Kuning. Prior to data collection, informed consent was obtained from all farmers involved in the survey. Participants were assured that their participation was voluntary, their responses confidential, and no personal or identifying information was recorded or disclosed. They were also informed of their right to withdraw at any time.

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